

# Time dependence of current-voltage measurements of $c$ -axis quasiparticle conductivity in 2212-BSCCO mesa structures

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We report four-point IV measurements of the  $c$ -axis conductivity of mesa structures of 2212-BSCCO, using a system with sub- $\mu$ s resolution along with multi-level pulses. These allow a test to be made for the presence of nonequilibrium effects. Our results suggest simple heating alone is important in measurements of this kind.

In the highly anisotropic high-temperature superconductor  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (2212-BSCCO), a linear array of intrinsic Josephson junctions is formed in the out-of-plane direction due to the almost-insulating layers separating the superconducting copper-oxide bilayers. To investigate conduction across such junctions, mesa structures can be fabricated by lithographic patterning on the surface of almost atomically flat cleaved surfaces of single crystals. Hysteretic multi-branched IV characteristics are observed; each branch corresponds to the expected irreversible characteristics of a junction in the measured array. [1]

In principle, the shape of the characteristics can be used to determine the  $c$ -axis quasiparticle conductivity and the superconducting energy gap. However, in many circumstances one observes regions in the IV characteristics with negative slope—“backbending”—and even an  $S$ -shaped feature. These cannot be described by simple theory, but have been attributed by some authors to nonequilibrium effects and by others to simple heating. In the past, pulsed measurements on 200–500 ns time scales have been used with this geometry in an attempt to circumvent possible problems from sample heating. (See Ref. [2] for corresponding references.)

We have made pulsed four-point IV measurements on a stack of  $(30\text{ }\mu\text{m})^2$  junctions with a system of cryogenically cooled buffer amplifiers with 50 ns time resolution. Square voltage pulses are applied to the sample via a series resistor. For more detail see Ref. [2]. Here we present data for an oxygen-annealed sample (Figs. 1 and 2) and for an as-grown sample from a different batch (Figs. 3 and 4). Both samples have around 30 junctions in the main stack.

Typical IV measurements are shown in Fig. 1. [3] We identify the drop in voltage with heating—the sample conductivity increases with temperature. Nonequilibrium effects are expected to vary on much shorter timescales. Figure 2 shows a series of IV measurements at various times after the switching-on of different-sized square current pulses. We believe the 50 ns characteristics approximate the intrinsic sample properties up to currents in excess of 20 mA. The 0.3 s characteristics are indistinguishable from dc measurements. The strong time-dependence of the shape of the characteristics shows

that the onset of the backbending feature is not associated with the gap voltage. We deduce the temperature on the heated curves by comparison with the 50 ns quasi-intrinsic characteristics at higher base temperatures, e.g., for a current of 15 mA, the sample temperature rises from 33 K to above  $T_c$  in  $\sim 10\text{ }\mu\text{s}$ .

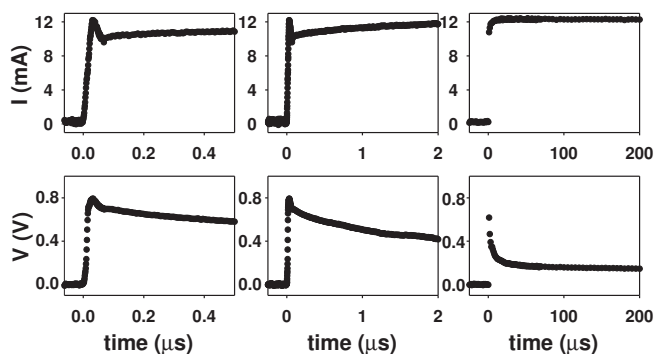


FIG. 1. Variation of sample current and voltage at 9 K for an applied simple square pulse of 4 V.

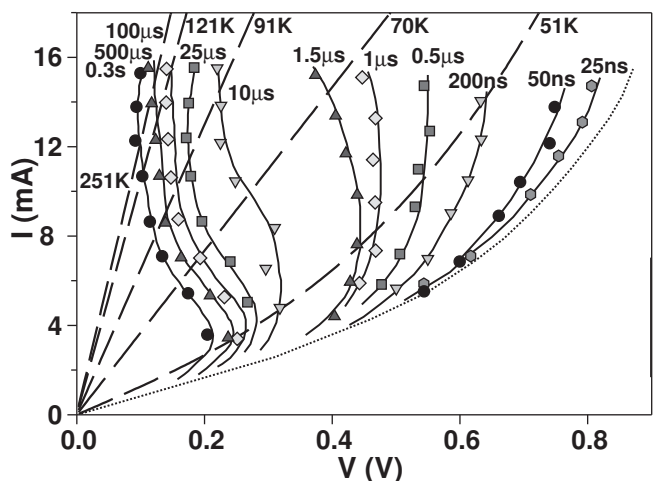


FIG. 2. Evolution of IV characteristics with time at a base temperature of 33 K. Dashed lines show fits to 50 ns IV characteristics at a number of base temperatures. Solid lines are guides for the eye. The form of the intrinsic characteristics at 33 K is suggested by the dotted line.

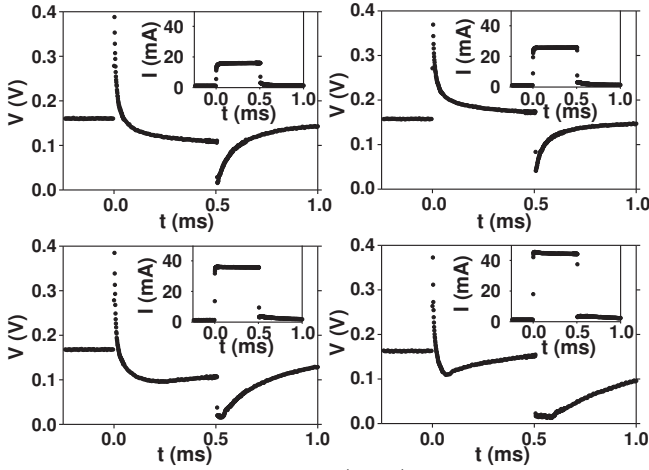


FIG. 3. Sample voltage and (inset) current for pulses with a low applied level of 0.5V and 500  $\mu$ s high applied levels of (a) 2V, (b) 3V, (c) 4V and (d) 5V, at a base temperature of 23 K. Note the small size of the current at low bias compared to its high-bias values.

Figure 3 shows measurements using high-bias pulse sequences superimposed on a non-zero low-bias level. The increase in low-bias sample voltage following the high-bias pulse is consistent with the mesa cooling back down—the low-bias conductivity decreases steeply from low temperatures towards  $T_c$  and varies only slowly around and above  $T_c$ . Examining the IV data in Figs. 3a–d, respectively 50  $\mu$ s and 0.4 ms after the start of the high-bias pulse, we find backbending and an  $S$ -shaped feature. In Figs. 3c and 3d, we note the transition from negative to positive slope, most likely associated with sample heating to well above  $T_c$ ; this conclusion is supported by the initial regime of approximately constant voltage after the high-bias pulse, which corresponds to the mesa being heated above  $T_c$ .

The mesa temperature just after the end of the high-bias pulse can be deduced from the low-bias sample voltage: this is calibrated using measurements made at long times after the high-bias pulse over a range of base temperatures. In Fig. 4, the circle symbols show IV measurements at the end of a 5  $\mu$ s high-bias pulse. We label these with the temperature inferred from the low-bias voltage shortly after the end of the high-bias pulse. The values are in good agreement with the temperature inferred from the position of the 5  $\mu$ s IV characteristics with respect to the 50 ns characteristics.

These results underline the consistency of invoking a thermal origin for observed backbending and  $S$ -shaped features, without positing additional nonequilibrium effects. These measurements and their analysis in terms of thermal models give us confidence in interpreting the short-time IV characteristics, and will enable us to obtain more reliable information on the intrinsic interlayer tunnelling, free from the effects of heating.

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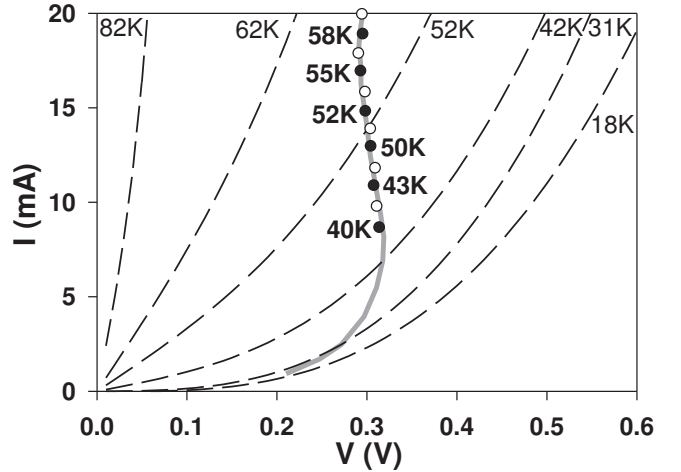


FIG. 4. IV characteristics just before the end of the 5  $\mu$ s high-bias pulse (circle symbols), at a base temperature of 18 K. The solid line is a guide for the eye. The labels beside alternate points (filled circles) indicate the temperature just after the end of the high-bias pulse, inferred from the resistance of the stack during the low level. Dashed lines show fits to 50 ns IV characteristics at a number of base temperatures.

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- [1] M. Tinkham, *Introduction to Superconductivity*, 2nd ed. (McGraw-Hill, Singapore, 1996).
  - [2] J.C. Fenton, P.J. Thomas, G. Yang, C.E. Gough, *Appl. Phys. Lett.* **80** (2002) 2535.
  - [3] The finite rise time and slight overshoot in the current and voltage reflect the “square” pulse shape from the signal generator.